to a separation tank, where insoluble tars are skimmed off of the water and fed back to the char combustor. A portion of the remaining water is used to rehumidify the synthesis gas prior to combustion in the gas turbine. This reduces the amount of water that must be treated and increases the power output from the plant. The remaining water is then treated in the wastewater treatment step.

Physical, chemical, and biological processes are the possible options for treating the wastewater streams. Further defined, physical operations are used to remove floatable and settleable solids, biological and chemical processes are used to remove most of the organic matter in the wastewater, and tertiary systems are used to remove any process constituents that are not taken out in secondary treatment. A combination of each of these was assumed to be used in the power plant. The concentration of organic chemicals from the power plant is anticipated to be low enough that secondary biological treatment will not be necessary, only primary treatment for solids removal. The wastewater is collected through a series of drains, trenches, and sumps that are connected to a main line. Collection systems such as this are generally open to the atmosphere, allowing some VOCs to be emitted. Many factors affect the rate of volatilization of organic compounds from the wastewater, including water surface area, temperature, turbulence, and concentration of organics, to name a few. Determining the rate of volatilization of each organic compound was not done for this study; thus, VOC emissions from wastewater were assumed to be zero.

5.0 Base Case Results by Impact Category

Although the material and energy balances for each of the three subsystems (biomass production, transportation, and electricity generation) were examined for each year of production, the resulting impacts were averaged over the life of the system to examine the relative percent of emissions from each. The average amount of emissions produced, resources consumed, and energy used by each of the subsystems per unit of energy delivered by the power plant can be seen in Tables 19 through 23. It should be noted that only the stressors that were of significant quantity are reported in these tables. Furthermore, these numbers appear to be definitive, while if data for a particular stressor were not available for all blocks, total stressors are being reported as lower than they actually are. The absence of data is specifically spelled out in this report.

In years negative seven through negative three all of the resources, emissions, and energy are associated with feedstock production. As expected, there is a yearly increase as the number of fields in production increases by one each year. The stressors then tend to be level in the positive years even with the construction and decommissioning activities associated with the farm equipment and truck transportation. Finally, a gradual decrease is seen, starting in year 23 when biomass production tapers off, leading up to a rapid decrease in impacts during final decommissioning. A majority of the resources, emissions, and energy are higher in years negative one and negative two due to the activities associated with plant construction.

	% of Total in this Table	% of Total in this Table Except CO2	% of Total in this Table Except CO2 and Isoprene	Total (g/kWh)	% of Total from Feedstock	% of Total from Transportation	% of Total from Power Plant
(a) Aldehydes	0.0%	0.0%	0.0%	1.68E-04	78.7%	17.9%	3.4%
(a) Ammonia (NH3)	0.1%	0.2%	2.0%	3.52E-02	99.9%	0.0%	0.0%
(a) Carbon Dioxide (CO2)	66.7%	0.0%	0.0%	4.59E+01	61.8%	12.0%	26.2%
(a) Carbon Monoxide (CO)	0.1%	0.4%	4.7%	8.30E-02	80.9%	13.0%	6.2%
(a) Chlorides (Cl-)	0.0%	0.0%	0.0%	6.60E-07	13.9%	2.0%	84.1%
(a) Fluorides (F-)	0.0%	0.0%	0.0%	8.08E-06	97.2%	0.3%	2.6%
(a) Non-methane hydrocarbons (including VOCs)	0.9%	2.6%	33.8%	5.95E-01	11.0%	1.3%	87.7%
(a) Hydrogen Chloride (HCl)	0.0%	0.0%	0.0%	2.05E-06	11.6%	1.6%	86.8%
(a) Hydrogen Fluoride (HF)	0.0%	0.0%	0.0%	3.81E-07	56.7%	3.3%	40.0%
(a) Hydrogen Sulfide (H2S)	0.0%	0.0%	0.0%	2.21E-08	56.6%	5.4%	38.0%
(a) Metals (unspecified)	0.0%	0.0%	0.0%	2.53E-09	53.2%	5.2%	41.6%
(a) Methane (CH4)	0.0%	0.0%	0.3%	5.07E-03	88.9%	4.2%	6.9%
(a) Nitrogen Oxides (NOx as NO2)	1.0%	3.0%	39.0%	6.86E-01	24.3%	3.9%	71.8%
(a) Nitrous Oxide (N2O)	0.0%	0.0%	0.5%	9.54E-03	95.8%	2.3%	1.9%
(a) Organic Matter (unspecified)	0.0%	0.0%	0.1%	1.06E-03	80.2%	4.3%	15.6%
(a) Particulates (unspecified)	0.1%	0.2%	2.4%	4.16E-02	56.4%	8.2%	35.4%
(a) Sulfur Oxides (SOx as SO2)	0.4%	1.3%	17.2%	3.02E-01	10.6%	2.2%	87.1%
(a) Tars (unspecified)	0.0%	0.0%	0.0%	7.69E-07	56.2%	5.4%	38.4%
Isoprene	30.8%	92.3%	0.0%	2.12E+01	100.0%	0.0%	0.0%

Table 20: Average Water Emissions per kWh of Net Electricity Produced

	% of Total in this Table	Total (g/kWh)	% of Total from Feedstock	% of Total from Transportation	% of Total from Power Plant
(w) Acids (H+)	0.0%	1.36E-05	99.3%	0.1%	0.6%
(w) Ammonia (NH4+)	12.2%	7.45E-03	100.0%	0.0%	0.0%
(w) Ammonia (NH4+, NH3, as N)	0.0%	6.92E-06	90.8%	1.4%	7.8%
(w) BOD5 (Biochemical Oxygen Demand)	0.5%	3.05E-04	98.4%	1.5%	0.1%
(w) Chlorides (Cl-)	0.0%	4.90E-06	30.7%	3.8%	65.5%
(w) COD (Chemical Oxygen Demand)	1.5%	9.12E-04	98.3%	1.5%	0.2%
(w) Cyanides (CN-)	0.0%	4.37E-08	84.3%	2.8%	13.0%
(w) Dissolved Matter (unspecified)	83.1%	5.09E-02	79.2%	18.6%	2.2%
(w) Fluorides (F-)	0.0%	6.74E-06	80.7%	2.9%	16.4%
(w) Hydrocarbons	0.0%	5.22E-08	100.0%	0.0%	0.0%
(w) Inorganic Dissolved Matter (unspecified)	0.0%	1.11E-06	56.4%	5.4%	38.2%
(w) Iron (Fe++, Fe3+)	0.0%	1.56E-09	55.4%	3.6%	41.0%
(w) Metals (unspecified)	0.0%	6.73E-07	56.2%	5.4%	38.5%
(w) Nitrates (NO3-)	0.0%	1.91E-07	55.4%	3.6%	41.0%
(w) Nitric acid	0.7%	4.13E-04	100.0%	0.0%	0.0%
(w) Nitrogenous Matter (unspecified, as N)	0.0%	2.21E-08	56.6%	5.4%	38.0%
(w) Oils	1.6%	9.80E-04	75.8%	13.9%	10.3%
(w) Organic Dissolved Matter (unspecified)	0.0%	4.41E-08	56.6%	5.4%	38.0%
(w) Phenol (C6H6O)	0.0%	1.33E-07	83.8%	2.8%	13.4%
(w) Sodium (Na+)	0.0%	8.08E-07	34.2%	3.7%	62.0%
(w) Sulfates (SO4--)	0.0%	8.13E-07	35.4%	3.7%	60.9%
(w) Sulfides (S--)	0.0%	8.73E-08	84.3%	2.8%	13.0%
(w) Suspended Matter (unspecified)	0.4%	2.40E-04	71.8%	5.7%	22.5%
(w) Tars (unspecified)	0.0%	1.10E-08	56.2%	5.4%	38.4%
(w) Water: Chemically Polluted	0.0%	3.80E-08	18.1%	2.5%	79.4%

Table 21: Average Energy Requirements per kWh of Net Electricity Produced

	Total (MJ/kWh)	% of Total from Feedstock	% of Total from Transportation	% of Total from Power Plant
Non-electric Energy Consumed by System	0.226664664	76.9%	15.8%	7.3%
Electricity Consumed by System	0.003906417	69.6%	6.4%	24.0%
Total Energy Consumed by System	0.230571081	76.8%	15.6%	7.6%

NOTE: The electricity produced and consumed by the power plant is not included in this table.
The power plant energy and electricity requirements are from upstream processes, construction, and decommissioning.

	% of Total in this Table	this Table Excluding Water	Total (g/kWh)	% of Total from Feedstock	% of Total from Transportation	% of Total from Power Plant
(r) Bauxite (Al2O3, ore)	0.0%	0.1%	0.00	30.1%	3.8%	66.2%
(r) Clay (in ground)	0.0%	0.0%	0.00	56.6%	5.4%	38.0%
(r) Coal (in ground)	0.1%	11.6%	0.78	67.2%	3.9%	28.9%
(r) Iron (Fe, ore)	0.1%	8.6%	0.58	84.3%	2.8%	13.0%
(r) Limestone (CaCO3, in ground)	0.0%	1.1%	0.07	87.1%	2.3%	10.7%
(r) Natural Gas (in ground)	0.0%	3.6%	0.24	95.2%	1.7%	3.1%
(r) Oil (in ground)	0.5%	65.0%	4.37	79.2%	18.5%	2.3%
(r) Phosphate Rock (in ground)	0.0%	0.9%	0.06	100.0%	0.0%	0.0%
(r) Potash (K2O, in ground)	0.0%	0.2%	0.02	100.0%	0.0%	0.0%
(r) Sand (in ground)	0.0%	0.0%	0.00	30.1%	3.8%	66.2%
(r) Sodium Chloride	0.0%	0.0%	0.00	33.0%	3.9%	63.1%
(r) Uranium (U, ore)	0.0%	0.0%	0.00	55.3%	3.6%	41.1%
Aluminum Scrap	0.0%	0.0%	0.00	30.1%	3.8%	66.2%
Iron Scrap	0.1%	9.0%	0.60	84.0%	2.8%	13.2%
Lubricant	0.0%	0.1%	0.00	67.9%	4.6%	27.5%
Trinitrotoluene	0.0%	0.0%	0.00	30.1%	3.8%	66.2%
Water Used (total)	94.9%		890.83	3.9%	0.1%	96.0%
Water: Unspecified Origin	4.4%		41.45	83.5%	3.2%	13.3%

Table 23: Average Solid Waste Generation per kWh of Net Electricity Produced

	% of total Waste	Total (g/kWh)	% of Total from Feedstock	% of Total from Transportation	% of Total from Power Plant
Waste (hazardous)	0.0%	0.00	40.7%	4.4%	54.9%
Waste (municipal and industrial)	24.5%	0.15	32.6%	8.7%	58.7%
Waste (unspecified)	75.5%	0.48	68.4%	3.6%	28.0%
Waste (total)	100.0%	0.63	59.6%	4.9%	35.5%

5.1 Air Emissions

Table 19 shows the majority of air emissions tracked in the LCA, averaged over the life of the system. Significant air emissions were found to come from all three subsystems, but primarily from the feedstock production and power plant subsystems. In terms of the total amount (not impact on the environment), CO_2 is emitted in the greatest quantity. Allocating the amount of atmospheric CO_2 absorbed by the biomass to the power plant, the percentages of total CO_2 emissions from the feedstock, transportation, and power plant subsystems, respectively, are 62%, 12%, and 26%. The CO_2 from the power plant subsystem is due to plant construction and decommissioning.

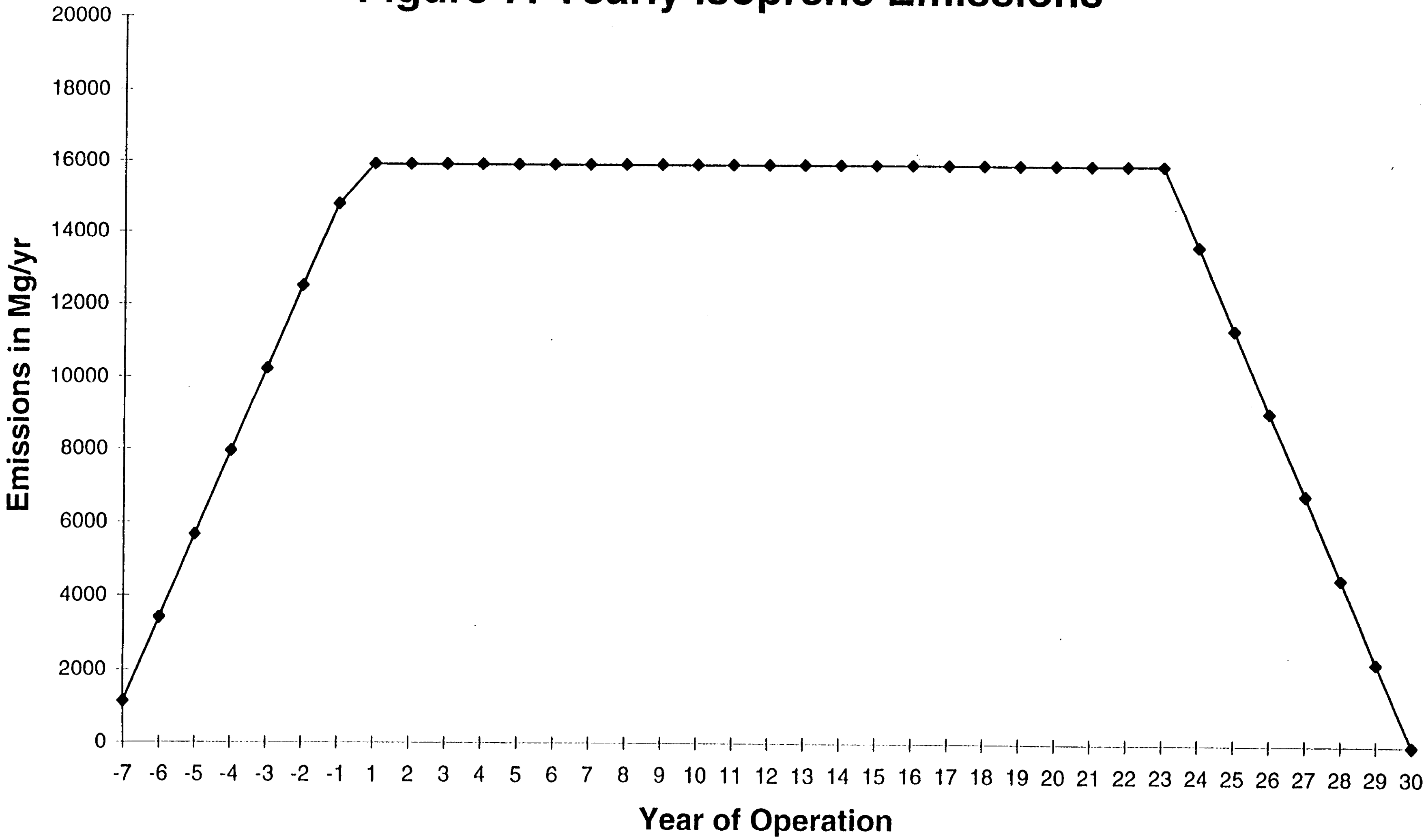
The second largest air emission is isoprene, the compound used to model biogenic emissions from the trees. Yearly isoprene emissions are shown in Figure 7. As expected, they were found to increase by one-seventh each year in the negative years, and decrease by one-seventh each year in years 23 through 30 when biomass production tapers off. It should be noted that simply because isoprene was emitted in the second greatest quantity, its total amount released and impacts are not necessarily large or significant. Further studies of actual releases and impacts should be done.

NOx and non-methane hydrocarbon (NMHC) emissions (including VOCs) are the next highest-released air emissions, followed by SOx. The quantities of all air emissions released from transportation are lower than from the rest of the system; the power plant produces the majority of SOx, NOx, and NMHC emissions. The majority of air emissions, besides CO_2 and isoprene, produced in the feedstock production section are typical of those from diesel-fueled farm equipment (e.g., methane, hydrocarbons, carbon monoxide, particulates); the total amount of these emissions is small in comparison to other emissions from the power plant. It should be noted that because of a lack of data, biomass decomposition during storage and transport was assumed to produce CO_2 rather than methane. The species released in a real situation will depend on the conditions that the biomass is subjected to as it decomposes. If it is kept in mostly aerobic environments, as is likely, little-to-no methane will be produced.

There are five major gaseous forms of nitrogen expected to be released from the biomass-to-electricity system. These include diatomic nitrogen (N_2), ammonia (NH_3), nitrous oxide (N_2O), nitric oxide (NO), and nitrogen dioxide (NO_2). N_2 was not included in the mass balances for this LCA; therefore, the other nitrogen compounds shown in Table 19 make up a much larger portion of total gaseous emissions than would really be the case. Because both participate in photochemical reactions, NO and NO_2 are collectively designated as NOx.

Three air emissions that are generally believed to have the potential to contribute to global warming were found to be emitted from this system. They are CO_2, CH_4, and N_2O. To determine the total global warming potential (GWP) from these compounds, weighting factors determined by the Intergovernmental Panel on Climate Change (IPCC) were applied. The GWP of a gas reflects its cumulative radiative capacity over a specified period of time. The numbers developed by the IPCC are based on a 100 year time frame. The recommended values, expressed as the GWP of a gas

Figure 7: Yearly Isoprene Emissions



relative to CO_2 on a mass basis, were 21 for methane and 310 for nitrous oxide (United Nations, 1996). CO_2, CH_4, and N_2O were found to be emitted from the system at rates of 45.9, 0.005, and 0.010 g/kWh, respectively. Applying the appropriate GWP factors, this equates to 45.9, 0.1, and 3.0 g CO_2/kWh, respectively. Thus, the total potential of this system to contribute to global warming is equivalent to 49 g of CO_2/kWh.

5.1.1 Carbon Dioxide Emissions

One of the most talked-about aspects of biomass energy is the potential reduction of atmospheric carbon dioxide per unit of energy produced. Because the carbon species released during gasification and combustion were originally removed from the atmosphere during the growing cycle, the net CO_2 emissions from the system have often been assumed to be zero. However, the picture is far more complicated, involving other carbon flows: carbon species are emitted in the processes involved in biomass production and transportation, carbon may be sequestered in the soil, and not all of the carbon in the biomass is converted to CO_2. Although it is certain that the net amount of CO_2 emitted from a biomass-based system is less than from fossil-fueled systems, biomass power is most likely not a zero-net CO_2 process. In the system being studied, CO_2 was emitted from farming operations that used fossil fuels, upstream energy consumption, transportation of the biomass to the power plant, and from the power plant itself.

The carbon closure of the system can be defined to describe the net amount of CO_2 released from the system in relation to the amount being recycled between the power plant and the growing trees:

$$CarbonClosure = 100 - \frac{Net}{Abs + Net} * 100 = 100 - \frac{Feed + Trans + PP}{Abs + Net} * 100$$

where:

- Net = the net amount of CO_2 released from the system after a credit is taken for the amount absorbed by the biomass in regrowth
- Abs = the CO_2 absorbed by the biomass during regrowth
- Feed = the CO_2 released from the feedstock subsystem, not including the credit taken for the amount absorbed by the biomass in regrowth
- Trans = the CO_2 released from the transportation subsystem
- PP = the CO_2 released from the power plant subsystem, not including the CO_2 emitted from gasification and combustion of biomass

Since fossil fuel use is the only source of CO_2 that is not counterbalanced by that absorbed by the biomass, a process that does not use any fossil fuels will have a 100% carbon closure. In other words, all CO_2 produced within the system would also be consumed by the system, producing a zero-net CO_2 process.

The question of whether the net CO_2 emissions were negative or positive was found to depend most heavily on the amount of carbon that could be sequestered in the soil. Literature data on the capacity of soil to retain carbon are not consistent (see section 4.1.8); moreover, such data are likely to be highly site-specific. Five studies relevant to the biomass-based system examined here report sequestration values ranging from -4.5 to 40.3 Mg C/ha over a seven year rotation, with the upper number generally seen to be a very special case. Because the actual amount sequestered will be highly site specific, and given the wide discrepancy of values in the literature, it is impossible to say what constitutes a representative value. Therefore, a sensitivity analysis, with a base case of zero sequestration, was performed. If the soil does not sequester or lose carbon, the system achieves approximately a 95% CO_2 closure. The net emissions for this base case scenario are equal to 254 kg CO_2/kW of plant capacity (46 g/kWh). Figure 8 shows the carbon closure for other values found in the literature. If the soil on which hybrid poplars are planted is able to sequester carbon at a rate above 1.9 Mg/ha over the seven year rotation, the CO_2 emissions from this system will be negative, resulting in a net removal of CO_2 from the atmosphere. Compared to the values found in the literature, then, very little carbon sequestration is necessary to obtain a zero-net CO_2 process. It should be noted that because of the release of other carbon species, such as carbon monoxide, methane, and hydrocarbons, the net *carbon* emissions into the atmosphere will always be higher than the net CO_2 emissions. However, CO_2 makes up over 99.97% (by weight) of all carbon-containing air emissions.

Figure 9 illustrates the average annual flows of CO_2 from the different parts of the system. Yearly CO_2 emissions are shown in Figure 10. Because the atmospheric CO_2 absorbed by the biomass is allocated to the feedstock production subsystem, the net amount emitted to the atmosphere decreases in the negative years as more biomass is planted; equal CO_2 absorption during each rotation is assumed. Because of plant construction, the increase in net removal of CO_2 is slowed in years negative one and negative two. CO_2 emissions in year one are less than the steady-state emissions in normal operating years because the power plant is operating at only 40% (50% of the normal 80%) capacity. CO_2 emissions increase beginning in year 23 as biomass production tapers off. Finally,because of credits taken for recycling power plant equipment, CO_2 emissions decrease substantially in year 30.

5.1.2 Air Emissions from the Power Plant: Non-Methane Hydrocarbons, NOx, and SOx

Yearly NMHC, NOx, and SOx emissions are shown in Figures 11 through 13. Each of these three graphs have similar shapes, showing that emissions increase rapidly once the power plant is operating at full capacity. It should be noted that the total amount of these three compounds released represents only 2.3% of the mass of all air emissions.

Except for the small amount emitted in electricity generation within the feedstock production subsystem, the majority of the overall system SOx and NOx, 87% and 72%, respectively, come from the power plant. The amounts emitted during normal operation are 26 g/GJ heat input (0.061 lb/MMBtu) and 50 g/GJ heat input (0.12 lb/MMBtu), respectively. Table 24 gives the standards of performance for new electric utility steam generating units using fossil fuels, taken from the Code of Federal Regulations (40 CFR 60.43a and 60.44a). For the base case of this study, which very conservatively assumed that all of the sulfur and nitrogen contained in the biomass was converted

Figure 8: Carbon Closure for Various Literature Values of Soil Sequestration

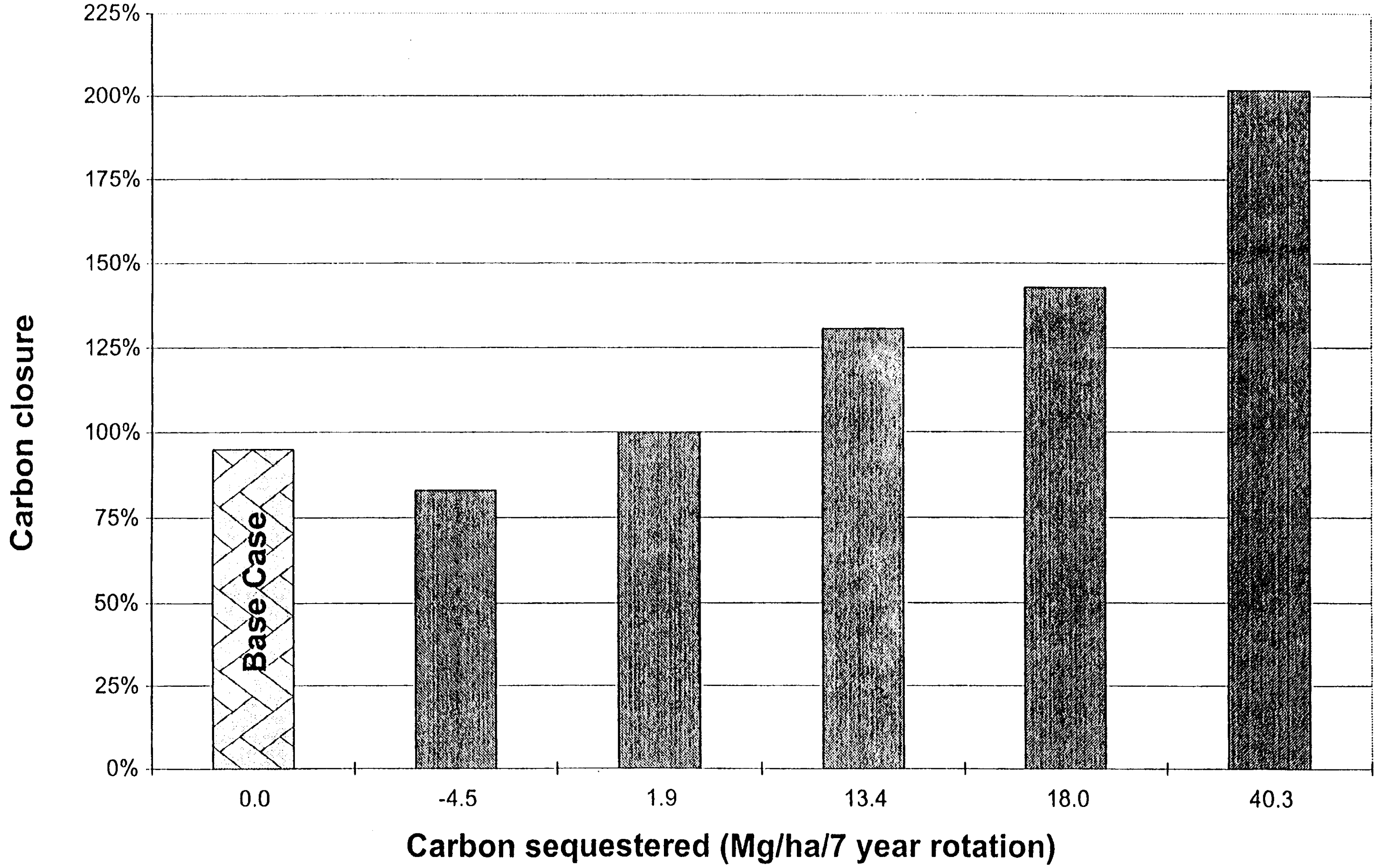


Figure 9: Life Cycle Flows of CO_2 within a Biomass Power System g CO_2 per kWh of Electricity (% of net)

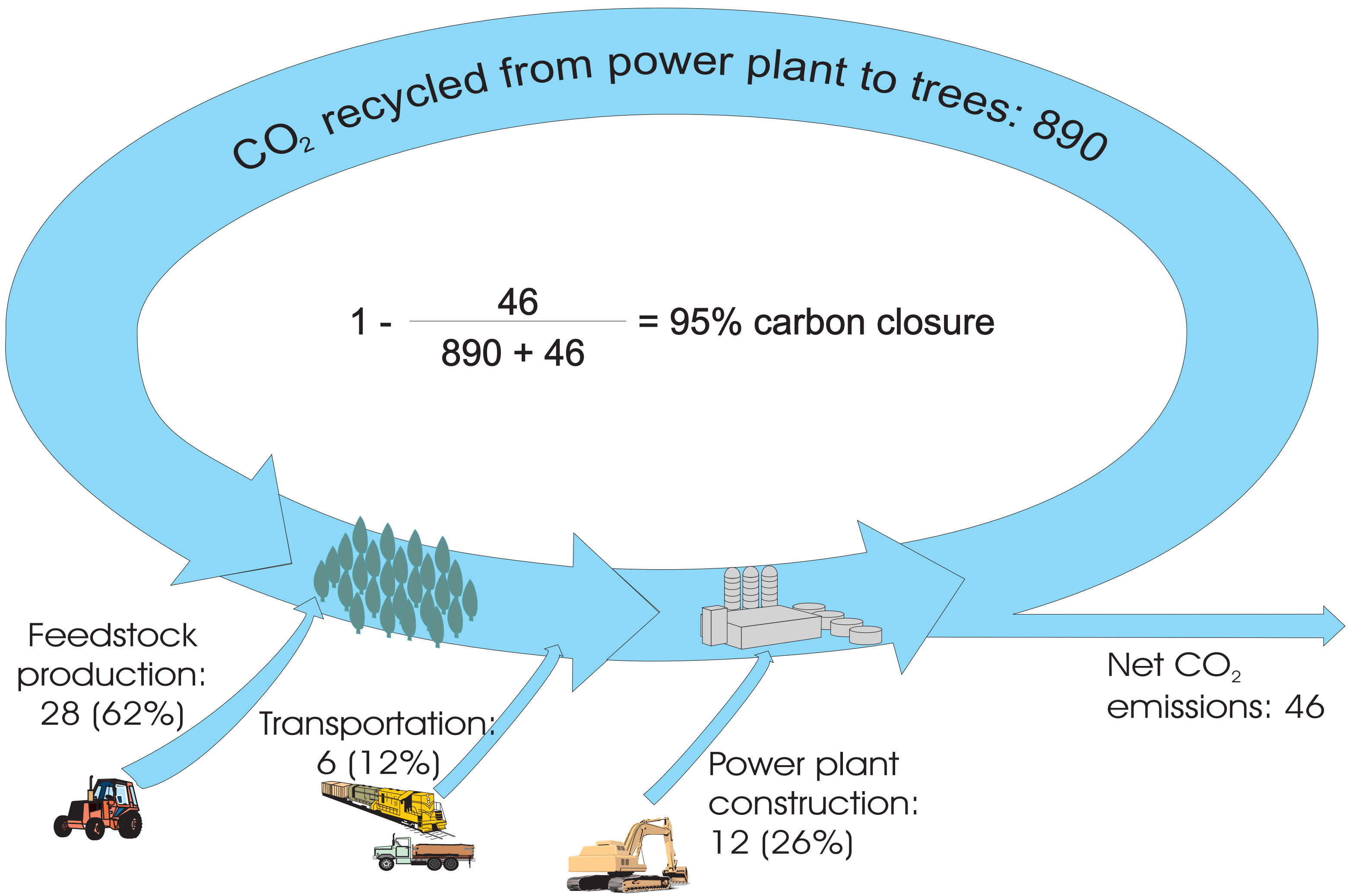


Figure 10: Net Yearly CO_2 Emissions Over the Life of the System

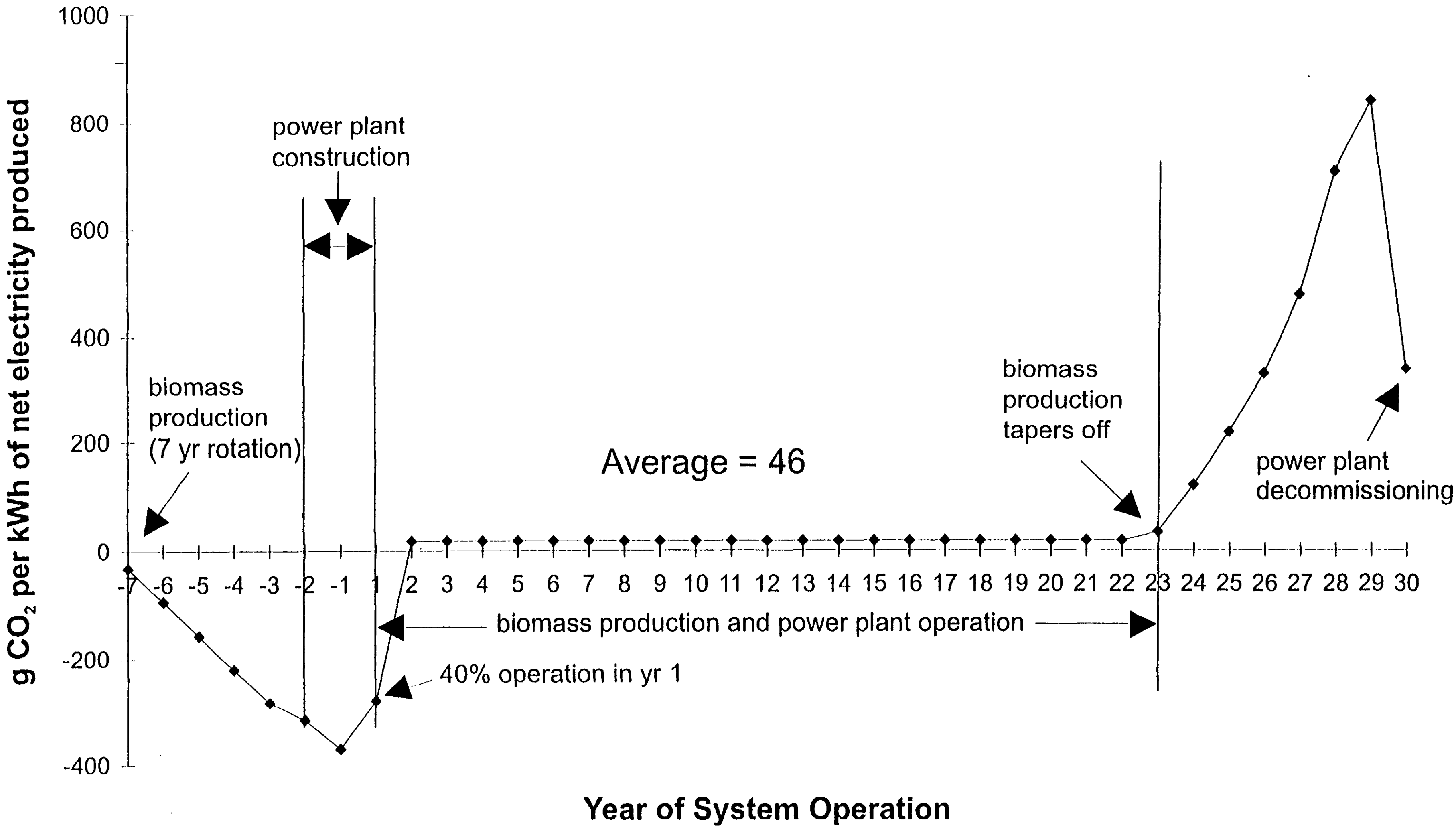
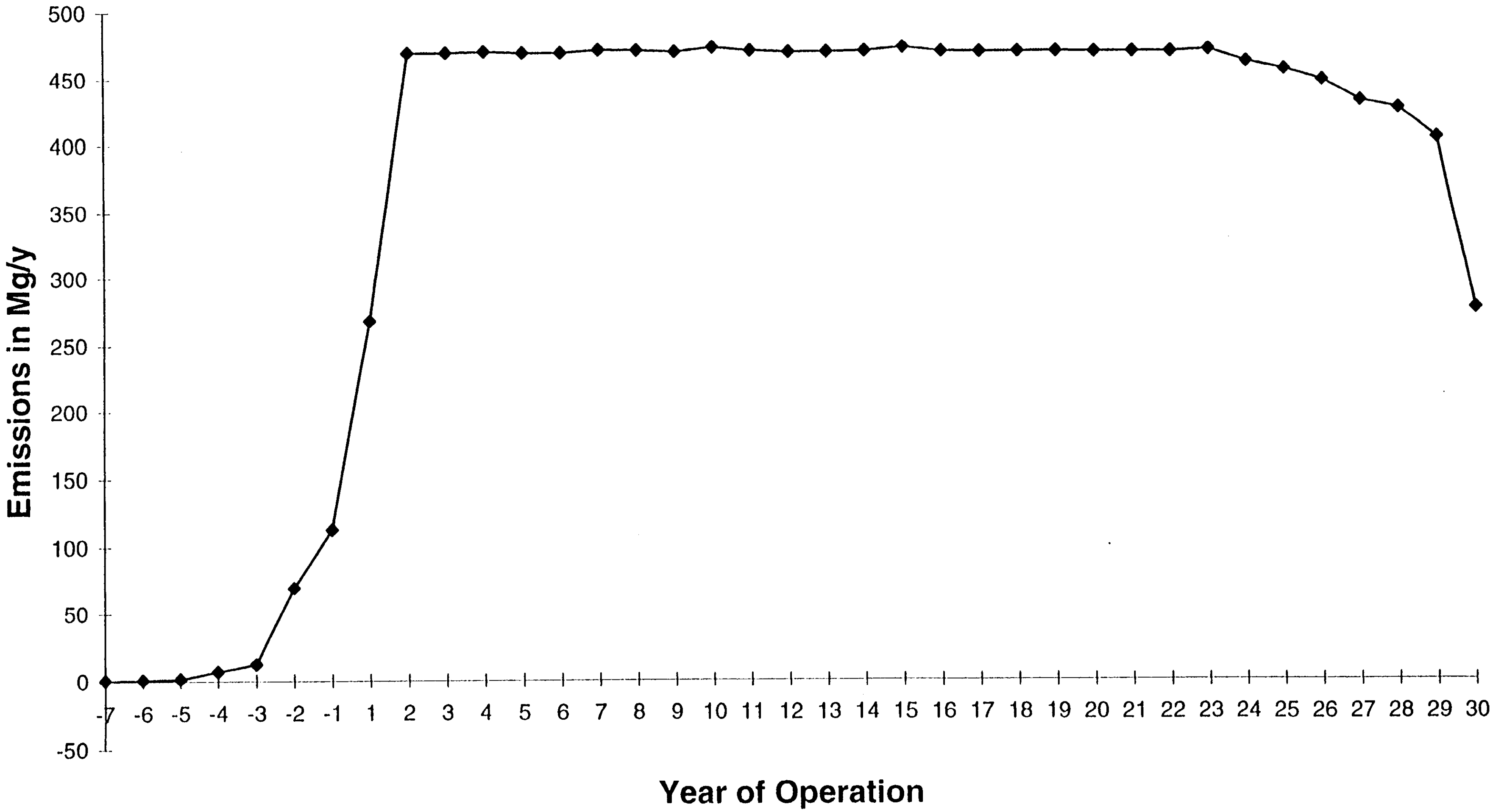


Figure 11: Yearly Non-Methane Hydrocarbon Emissions Including VOCs



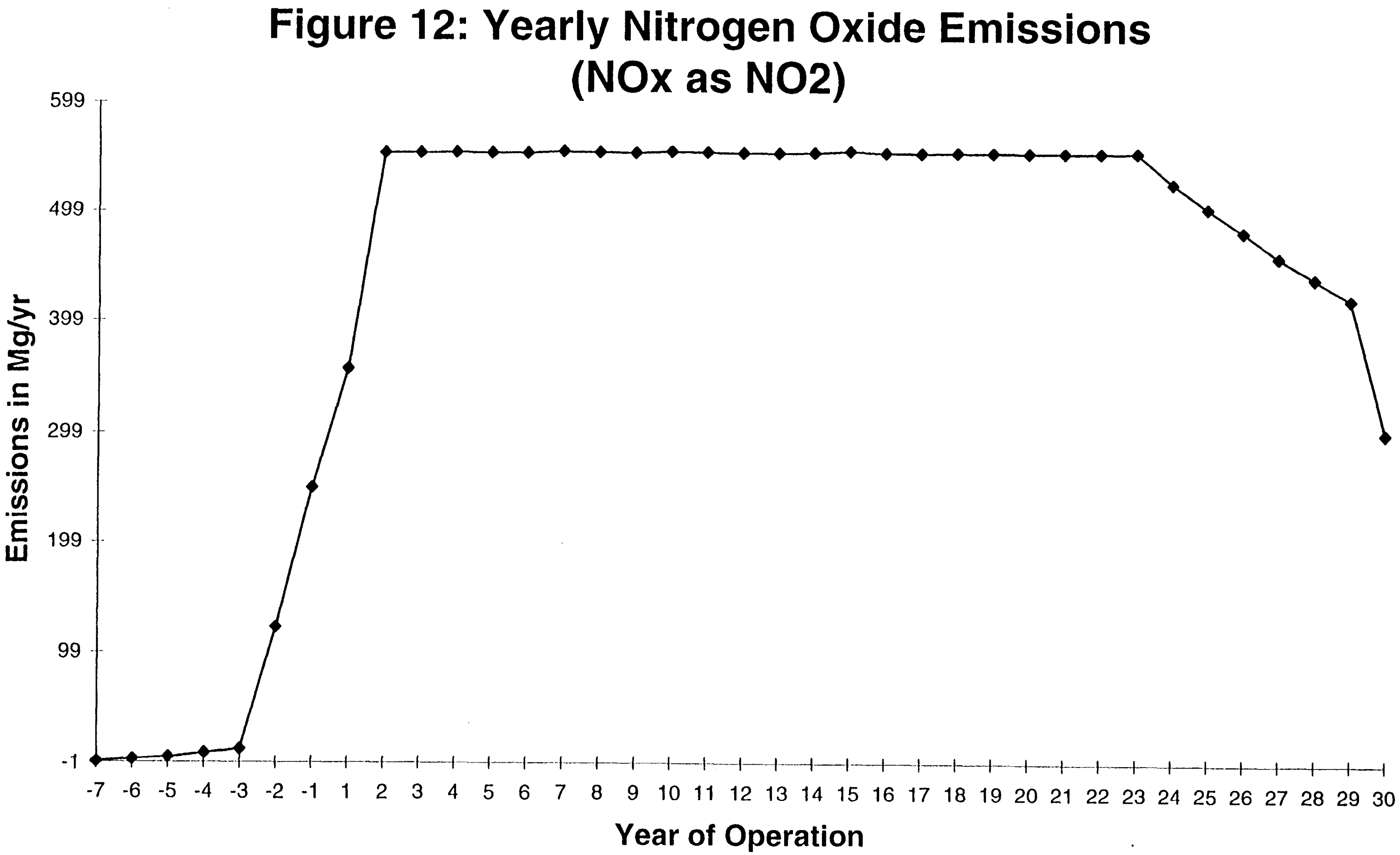
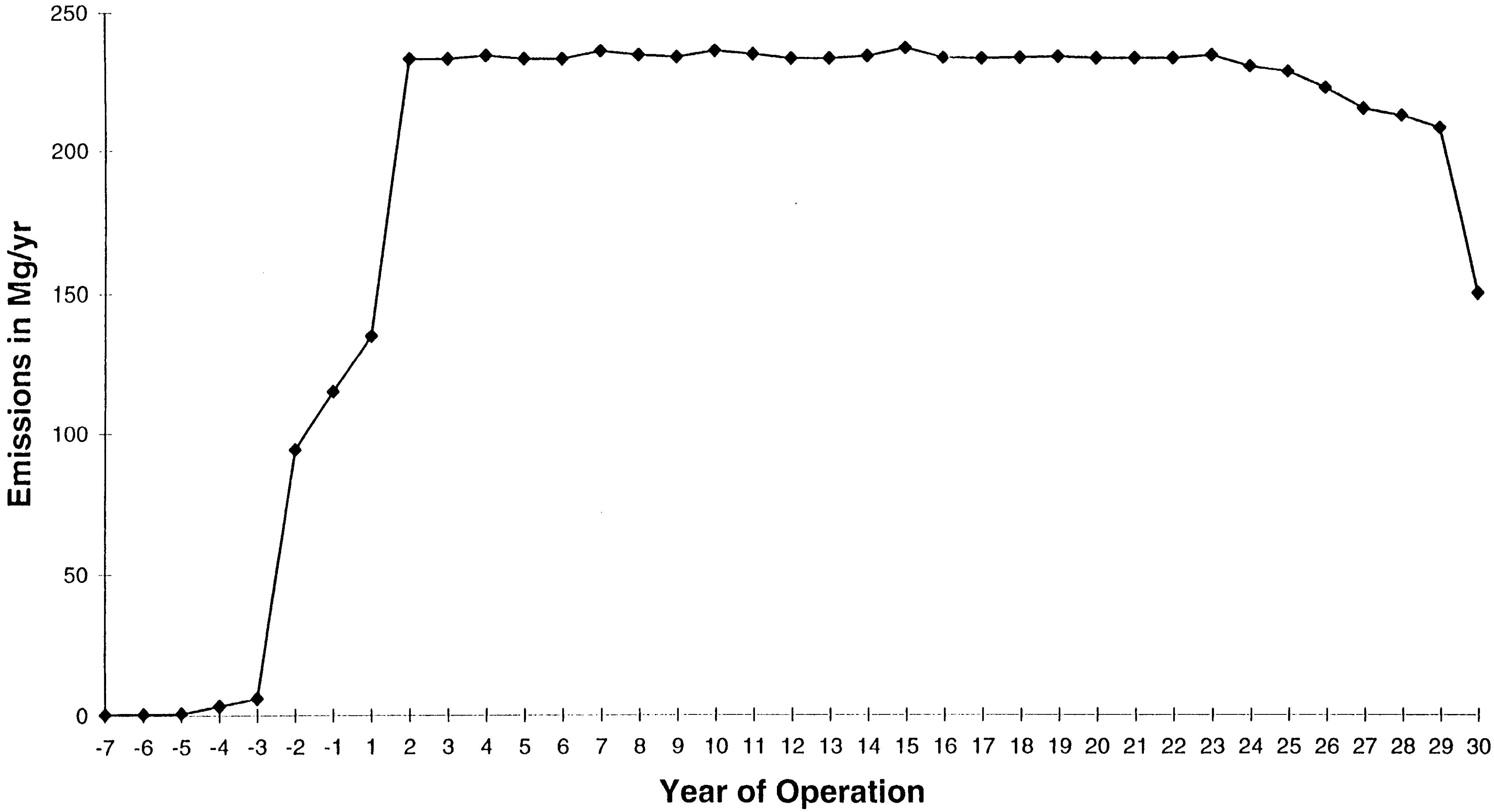


Figure 12: Yearly Nitrogen Oxide Emissions
(NOx as NO2)
Emissions in Mg/yr
599
499
399
299
199
99
-1
-7 -6 -5 -4 -3 -2 -1 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Year of Operation

Figure 13: Yearly Sulfur Oxide Emissions (SOx as SO2)



to SOx and NOx, the SOx emissions are one-tenth of the New Source Performance Standard (NSPS) requirement and the NOx emissions are one-fifth of the NSPS requirement.

Table 24: New Source Performance Standards for Fossil-Fueled Power Plants

	g/GJ heat input, HHV (lb/MMBtu)		
	Gaseous fuels	Liquid fuels	Solid fuels
NOx	coal-derived 215 (0.50) all other 86 (0.20)	coal-derived 215 (0.50) shale oil 215 (0.50) all other 86 (0.20)	coal-derived* 215 - 344 (0.50 - 0.80) all other 258 (0.60)
SOx	86 (0.20)	86 (0.20)	258 (0.60)

* Allowable emissions depend on the type of coal.

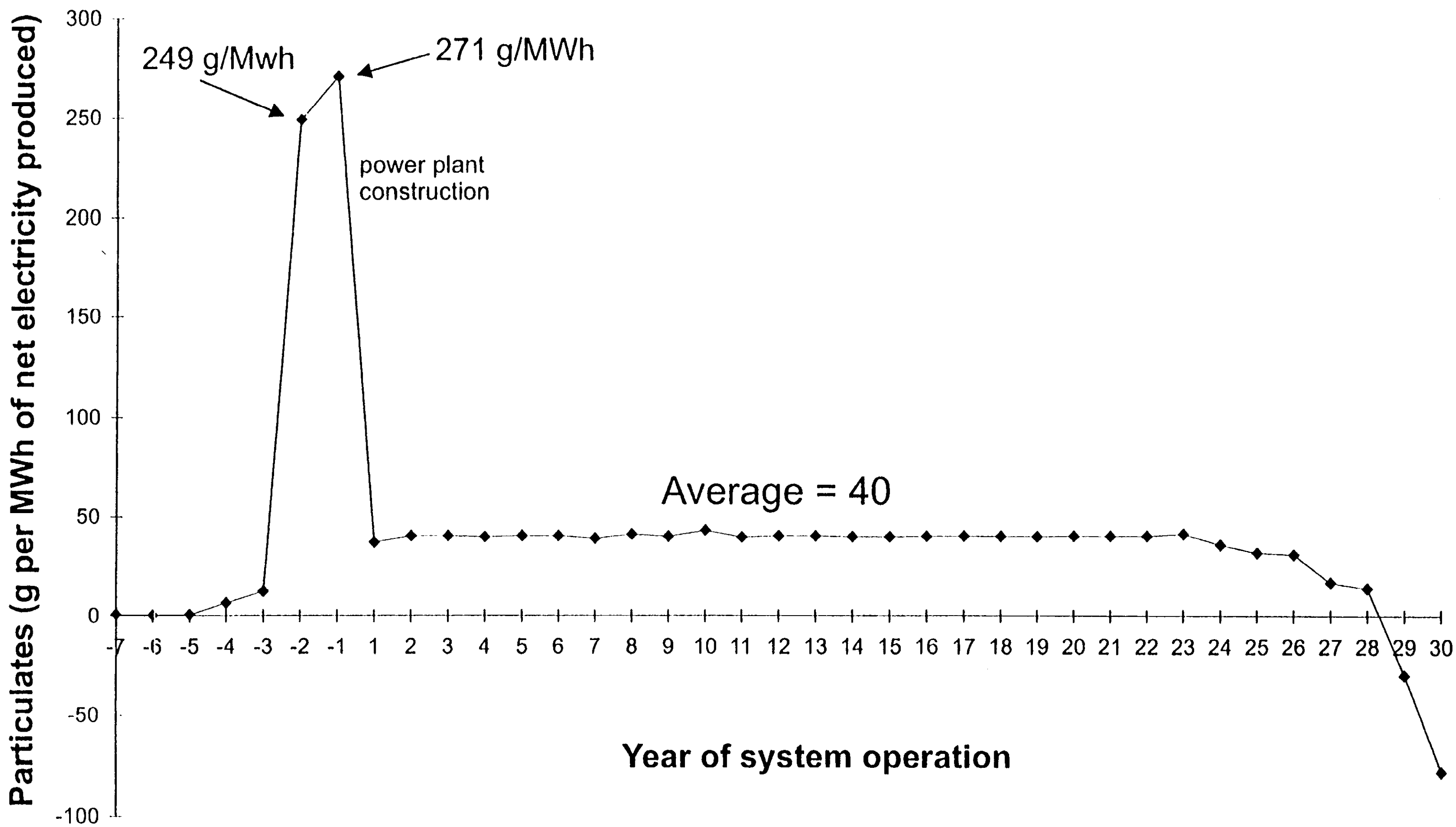
5.1.3 Particulate Emissions

Particulate matter is a collective term used to describe very small solid and/or liquid particles. Particulates are produced by diesel-fueled farm equipment and during power plant construction and operation. The average amount emitted over the life of the system is 40 g/MWh of energy produced/year (232 kg/year/MW of plant capacity), which represents only 0.06% of the total air emissions (by weight) and only 0.18% excluding CO_2 (Table 19). Figure 14 shows, however, that during the two years of plant construction, 249 and 271 g/MWh (1,380 and 1,500 kg/year/MW of plant capacity) of particulates are emitted. Impacts associated with particulate emissions will be more significant in these years than in any other during the life of the system.

According to the Code of Federal Regulations (40 CFR 60.42a) the NSPS for particulates from a new power plant fueled with any combination of gaseous, liquid, or solid feedstock is 13 g/GJ of heat input (0.03 lb/MMBtu). The amount of particulates emitted from the power plant in this study during normal operation is 0.47 g/GJ (0.0011 lb/MMBtu). Therefore, the power plant is well below the amount of allowable emissions. Note that these emissions are from the power plant only and do not include any of the upstream processes involved in feedstock production. Likewise, upstream process emissions are not included in the NSPS.

Wood dust is created where mechanical means are used to cut, shape, or otherwise change the size of wood products. Because of a lack of data, the dust emitted in chipping and moving the biomass was not included in this assessment. Storage of biomass also creates environments for the proliferation of microorganisms including mold, fungi, and associated spores that may induce allergic reactions. Perlack *et al* (1992) list two potential problem microorganisms associated with moulding wood (originally reported in Egeneus and Wallin (1985)). Jirjis (1997) reports that the microorganisms most seen with stored wood chips are moulds and actinomycetes. Associated respiratory diseases of varying symptoms, severity, and long-term effects are discussed. It is likely that by storing the biomass in whole-tree form until shortly before it is needed by the power plant, the health effects of rotting wood can be minimized.

Figure 14: Yearly Particulate Emissions Over the Life of the System



5.1.4 Carbon Monoxide Emissions

Carbon monoxide emissions represent only 0.4% of the mass of the total air emissions excluding CO_2. The annual releases are shown in Figure 15. The main source of this stressor is fossil fuel use in the feedstock production subsystem.

5.2 Water Emissions

Most emissions to water from the system occurred in the feedstock production subsystem, although the power plant produces a significant amount of water that is treated in-house. About 93%, by weight, of the water pollutants produced in the feedstock subsystem come from diesel oil production; 6% come from ammonium nitrate production. In general, though, the total amount of water pollutants was found to be small compared to other emissions. Table 20 shows that dissolved matter and ammonia (NH_4+) make up 83% and 12% of all water emissions. It should be emphasized that because of data unavailability, emissions of fertilizer and herbicide into water systems surrounding the plantation were not included in the life cycle assessment and therefore are not included in this table. However, if riparian filter strips are used, a significant portion of the fertilizers and herbicides that dissolve in surface waters can be removed before passing beyond the boundaries of the plantation (see Sears, 1996, for a detailed discussion on the ability of such strips to reduce effects on surface waters).

5.3 Energy and Resource Consumption

Yearly energy consumption for the system is shown in Figure 16, while average energy flows are shown in Figure 17. Use is highest in year negative one because of plant construction, and is negative in year 30 because of credits taken for recycling during decommissioning. A breakdown of energy consumption by the three subsystems is shown in Table 21. Not including power plant parasitic losses, feedstock production accounts for 77% of the system energy consumption. In order to study the energy budget of this system, three types of efficiencies can be defined. First, the traditional definition of energy efficiency gives the fraction of energy in the feedstock to the power plant that is delivered to the grid. The system studied was found to have a power plant efficiency of 37.2% (higher heating value basis). The life cycle efficiency, which includes the energy consumed by all upstream processes, is then defined as follows:

$$LifeCycleEfficiency = \frac{Eg - Eu}{Eb}$$

where:
- Eg = electric energy delivered to grid
- Eu = energy consumed by upstream processes
- Eb = energy contained in the biomass fed to the power plant.

Figure 15: Yearly CO Emissions

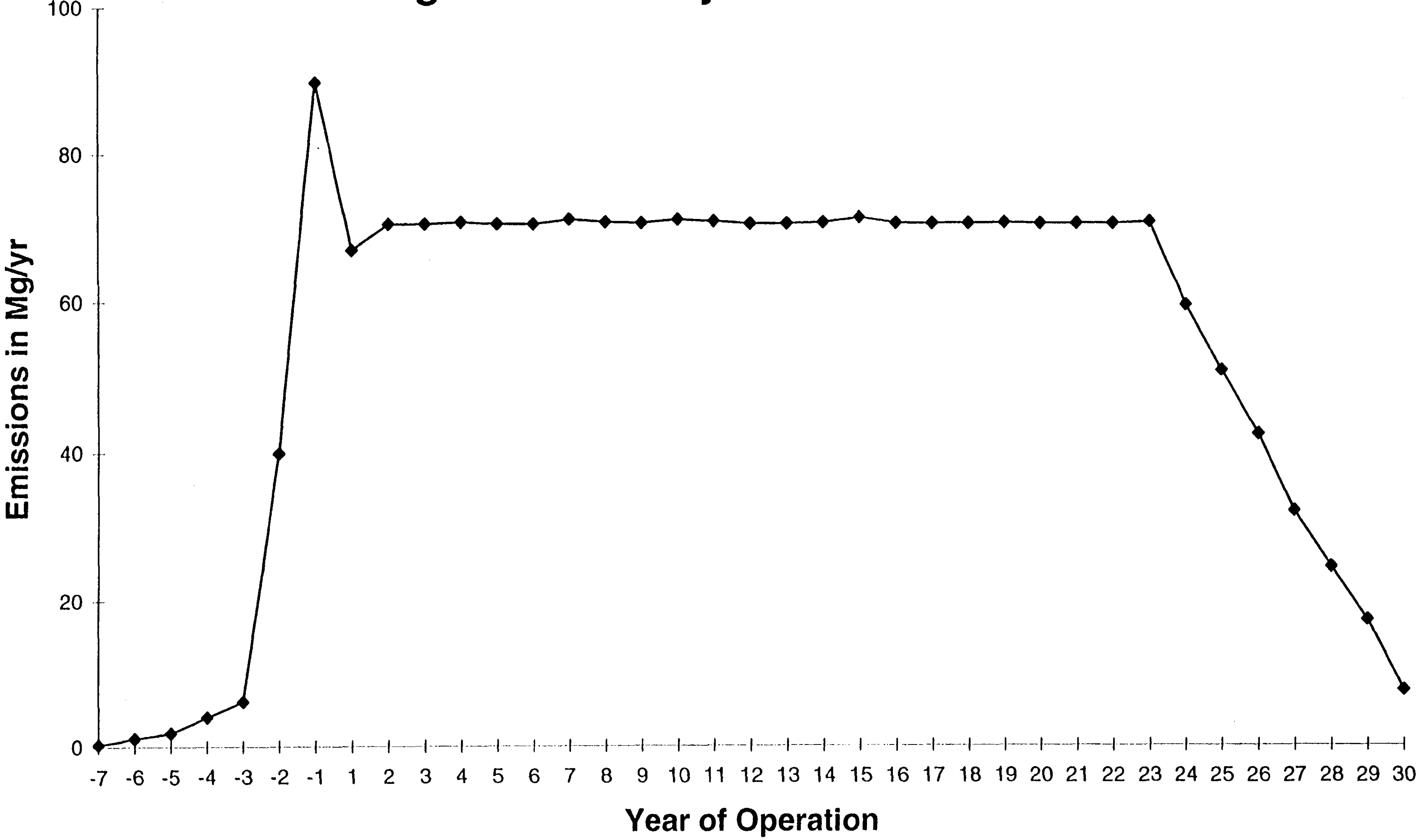


Figure 16: Yearly Total Energy Consumption Over the Life of the System

(Note: Electrity produced and consumed by the power plant not included)

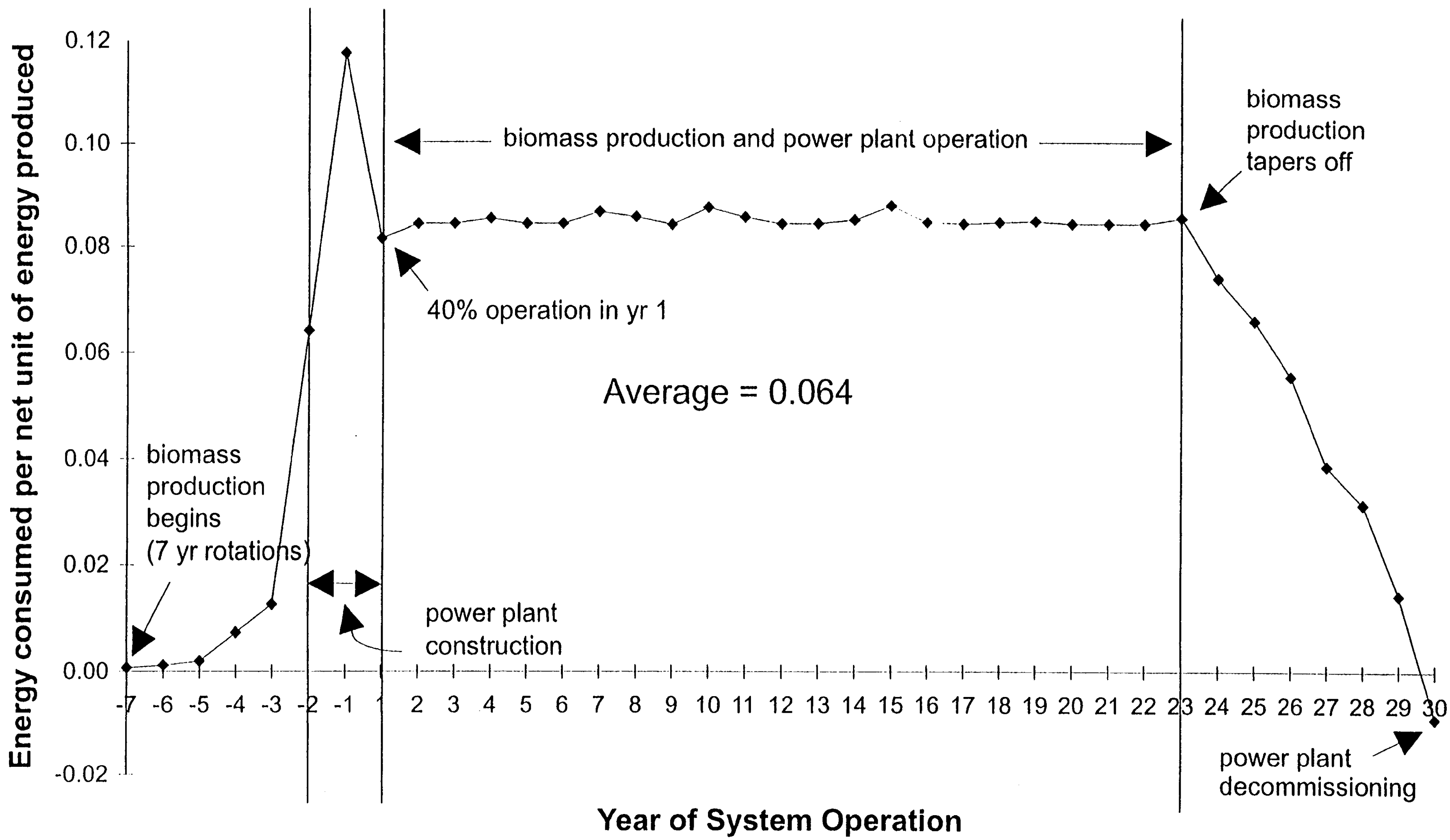
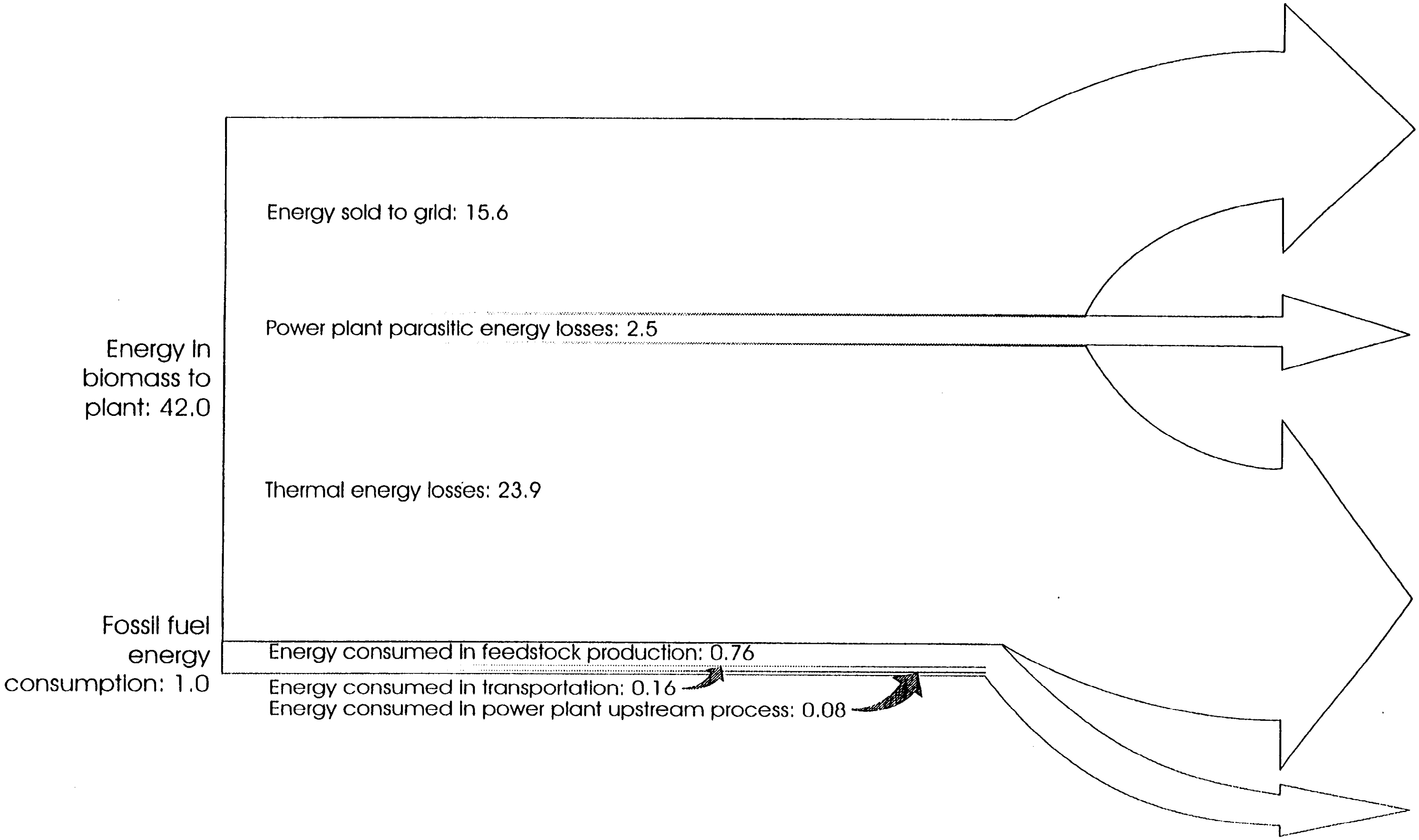


Figure 17: Life Cycle Energy Flows within a Biomass Power System (per one unit of fossil fuel energy consumed)



Note: Drawing is to scale therefore the breakdown of fossil fuel energy is difficult to depict with individual arrows.

The life cycle efficiency for this operation is equal to 34.9%. To understand how much energy is produced for each unit of fossil fuel energy consumed, a net energy ratio is calculated:

$$NetEnergyRatio = \frac{Eg}{Eff}$$

where: Eg = electric energy delivered to grid
Eff = fossil fuel energy consumed within the system.

This ratio does not take into account any renewable resource energy, since by definition, renewables are not considered to be consumed within the boundaries of the system. For this operation, the net energy ratio was found to be equal to 15.6. Thus, significantly more energy is produced than consumed.

In the context of this life cycle assessment, the term resource refers to any material consumed within the system boundary. Energy is not included in this term because it is accounted for by including the material that was used to produce it. From a life cycle viewpoint, renewable and sustainable are the same, and will be defined to be a substance replenished at a rate equal to or greater than its rate of consumption. Therefore, the biomass and its associated energy are not considered to be consumed by the system since they are also generated by the system. It is important to note that a substance is either termed renewable or non-renewable, and that its classification within these two groups is not dependent on the size of the remaining reserve. In assessing resource depletion in the inventory and impact portions of this study, the effects on society as a result of dwindling stock reserves were not assessed. Similarly, no estimations of the total reserve available were made.

Table 22 shows that water accounts for the vast majority of all resources consumed by the system. Excluding water use, oil, iron (ore and scrap), and coal account for 65%, 18%, and 12%, respectively, of the total resources (by weight). As expected, feedstock production requires the majority of the fossil fuels used in the system. The percentage of the total consumption of coal, natural gas, and oil used in the feedstock subsystem equals 67%, 95%, and 79%, respectively. Because of equipment manufacturing and construction, the power plant was found to require more electricity, and thus more coal and natural gas, than biomass transportation. However, the amount of oil consumed in transportation is higher than in the power plant subsystem. The annual requirements of oil, coal, and natural gas are shown in Figures 18 through 20. Figure 21 is also shown because iron, from ore and scrap, was consumed in significant quantities compared to other resources.

Figure 18: Yearly Oil Consumption

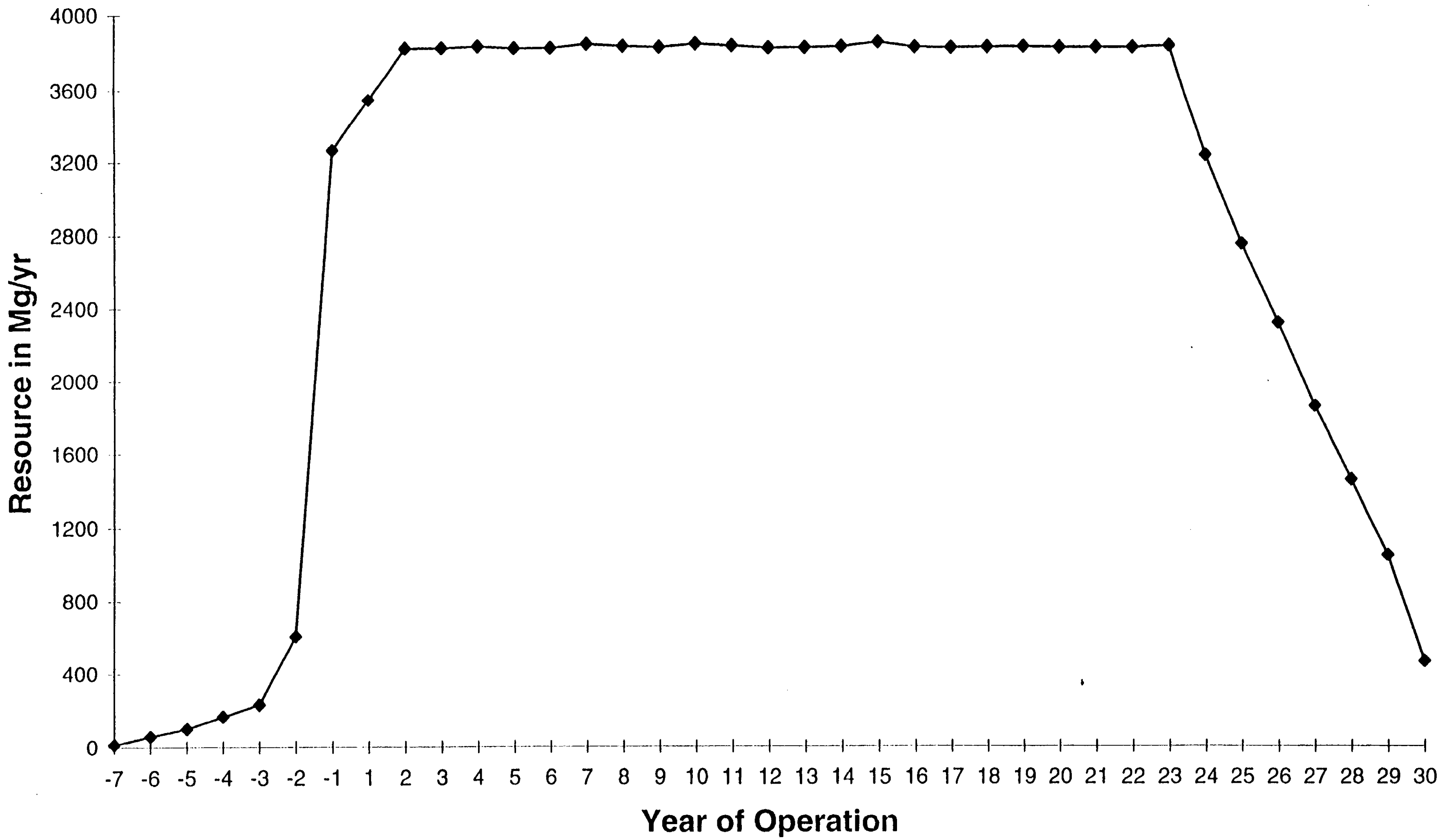


Figure 19: Yearly Coal Consumption

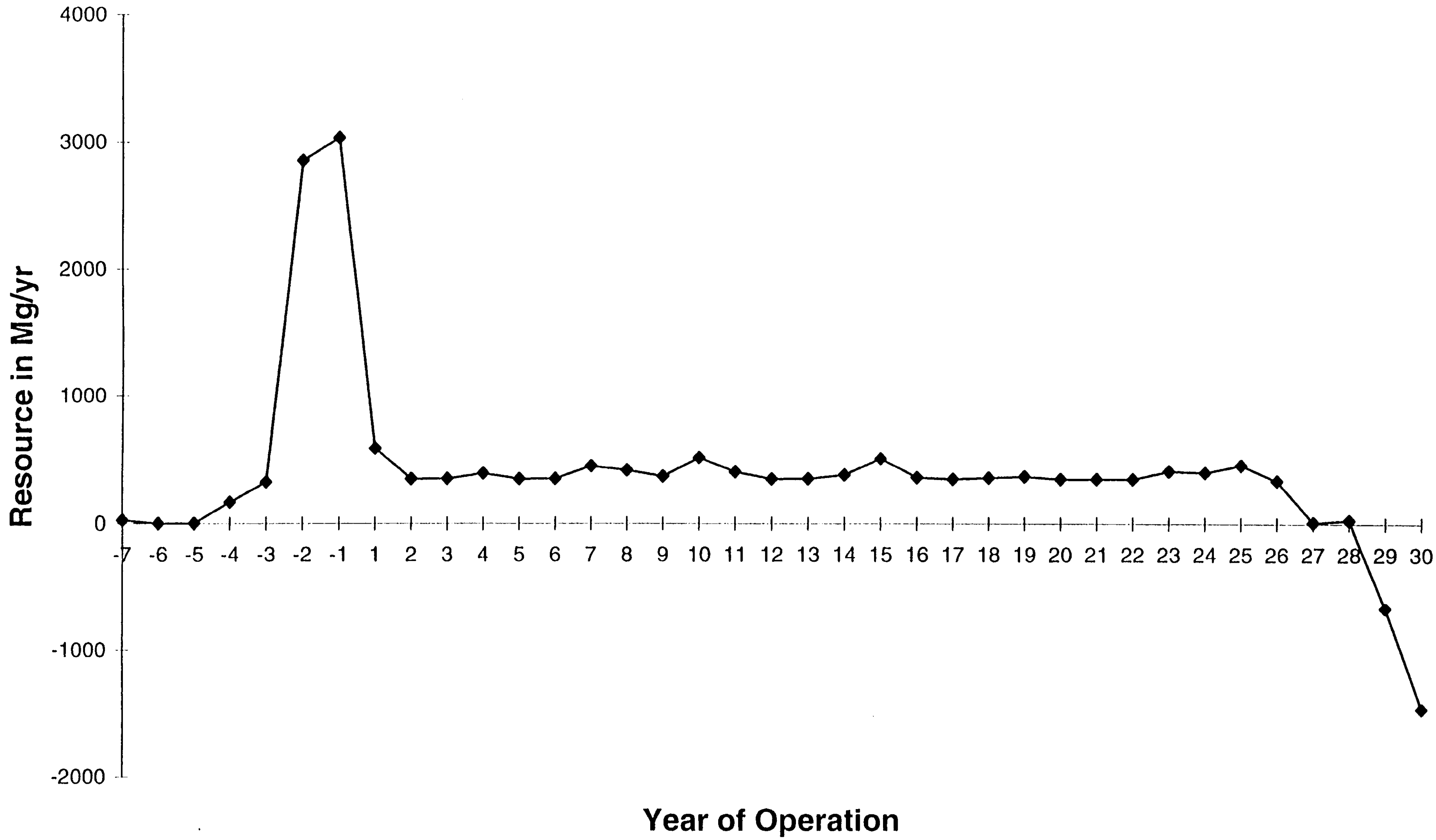


Figure 20: Yearly Natural Gas Consumption

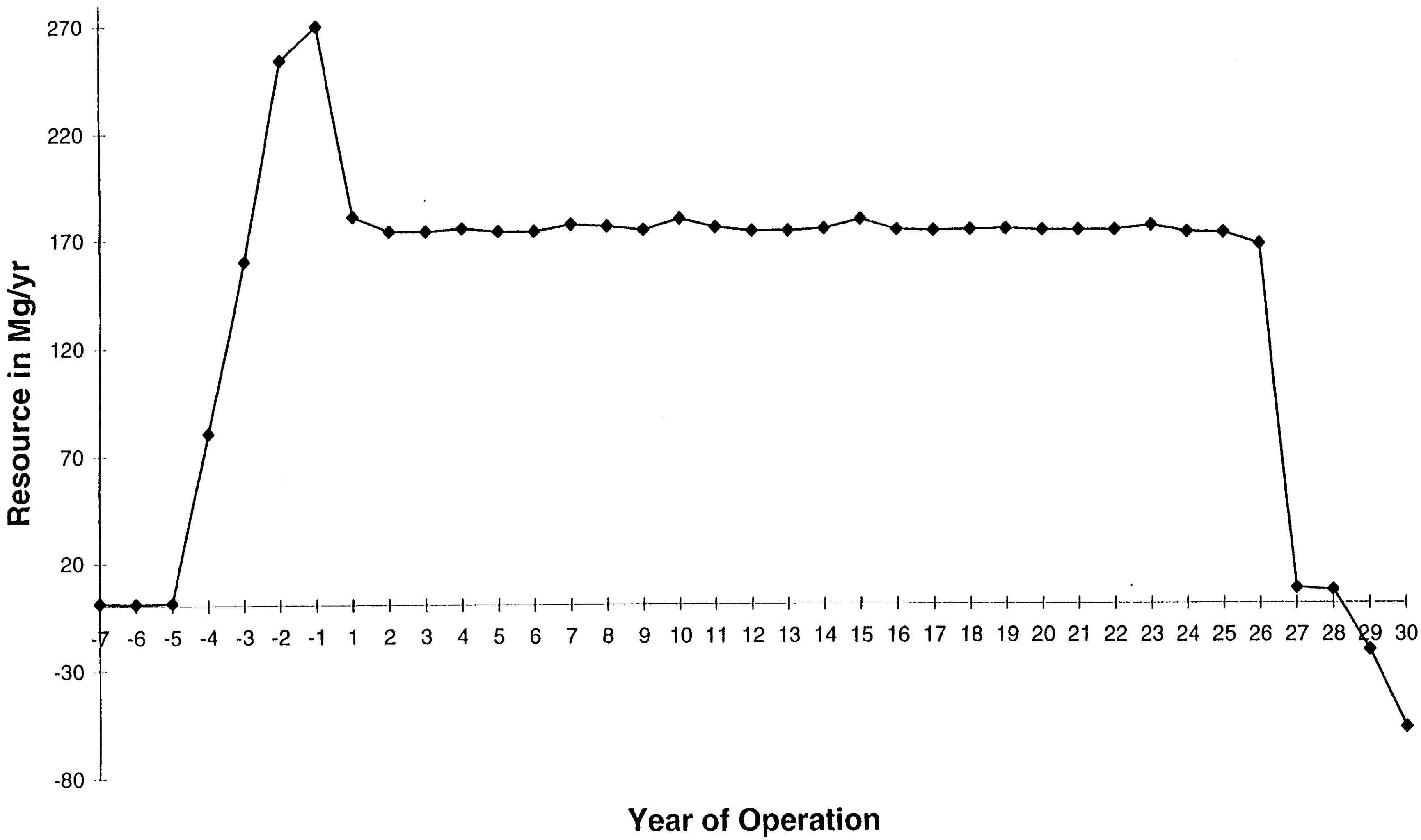
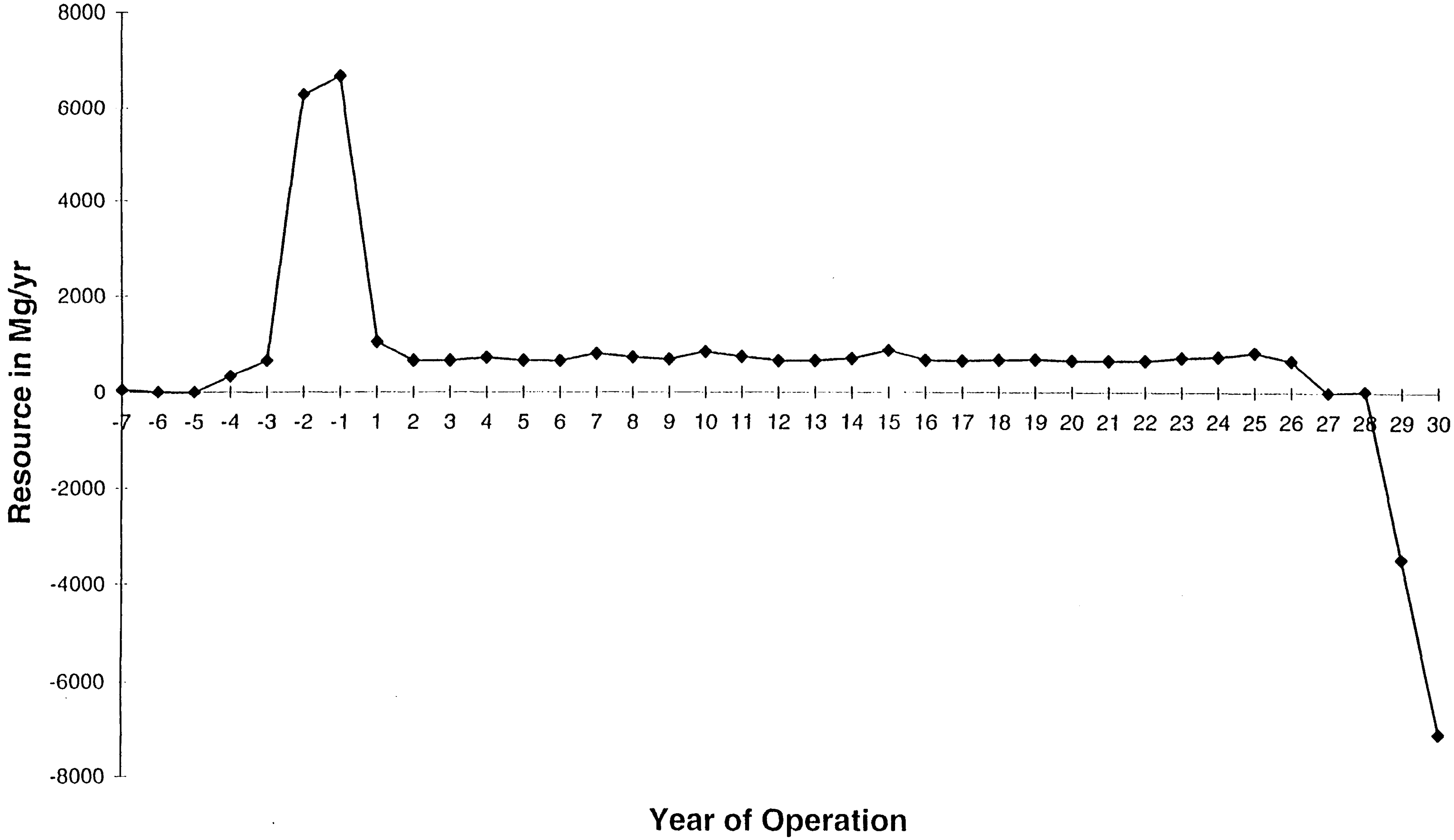


Figure 21: Yearly Iron Consumption (ore + scrap)



5.4 Solid Waste

Figure 22 shows the annual production of solid waste from the system. Non-hazardous solid waste was found to be the only solid waste produced in any significant quantity. TEAM defines several types of waste, and reports that unspecified, and municipal and industrial, can be combined to represent non-hazardous (See Table 23). The yearly variation in solid waste generation is the result of intermittent decommissioning and production of trucks and farm equipment.

6.0 Results Specific to the Three Major Subsystems

6.1 Base Case Feedstock Production Results

As stated earlier, feedstock production accounts for 77% of the non power-plant system energy consumption. Figure 23 shows that fossil fuel use in farming operations consumes the majority of this energy (83% of feedstock energy, 64% of total system energy). The second largest consumer of energy is the transportation of fertilizers and herbicides to the field. This accounts for 9% of feedstock energy and 7% of total system energy consumption. Because of the natural gas required to manufacture ammonium nitrate and urea, fertilizer production accounts for 6% of the energy used in the feedstock production subsystem, and 5% of the total system energy.

Figure 24 shows the source of CO_2 emissions in feedstock production, excluding that absorbed by the biomass. As expected, diesel fuel combustion in farming operations accounts for most of the CO_2 emitted (79% feedstock, 49% system). Diesel fuel production, which includes extraction and processing, emits 7% (4% system), while farm chemical transportation emits 9% (5% system). CO_2 is emitted from natural gas reforming operations in nitrogen fertilizer production.

Particulate emissions in feedstock production are shown in Figure 25. Although the combustion of fossil fuels in tractors and chippers emits the majority of the particulates to the air (56% feedstock, 31% total), those from transportation of chemicals to the farm were also found to be significant (31% feedstock, 18% system). Additionally, because of prilling operations and coupled energy use, ammonium nitrate manufacturing produces 7% of the total particulates released in feedstock production, and 4% from the entire integrated system.

Non-methane hydrocarbon emissions (including VOCs) for the feedstock production subsystem are shown in Figure 26. The majority (45% of feedstock and 5% of system NMHC emissions) are released during diesel oil combustion, but it's interesting to note that one-third are emitted in extracting crude oil and producing diesel fuel. Farm chemicals transport also emits a significant fraction of feedstock NMHC.